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Properties of Basalt Fiber-reinforced Lightweight Geopolymer Mortars Produced with Expanded Glass Aggregate

Adil GULTEKİN[1*]

[1]*Duzce University, Faculty of Engineering, Department of Civil Engineering, Duzce, Turkiye (ORCID: 0000-0002-5267-5312)*

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Abstract

Geopolymers are environmentally friendly binders with high mechanical properties and good durability characteristics. The advantages provided by geopolymers can be combined with the benefits of lightweight concrete. However, the number of studies on geopolymers produced with lightweight aggregates is limited. This study investigated the properties of fly-ash based geopolymer mortars prepared with expanded glass aggregate, as well as the influence of fiber addition on these mortar properties. For this purpose, fresh unit weight, water absorption, compressive strength and high-temperature resistance (upon exposure to 900°C) of the mortars were determined. The inclusion ratios of fibers were 0.1%, 0.2% and 0.4% by volume. Sodium silicate and sodium hydroxide were used as activators, and curing was carried out at 90°C for 24 hours in a laboratory-type oven. In addition to lightweight mortars, conventional geopolymer mortars were produced with limestone aggregate with similar gradation, and the obtained results were compared. The results have shown that the compressive strength of the reference mortar was 31.9 MPa, the use of expanded glass aggregate reduced the strength to 8.2 MPa, meanwhile, the fresh unit weight decreased by approximately 50%. After the high-temperature experiment, the compressive strength of the reference mortar decreased by 40%, while the strengths of lightweight mortars increased in the range of 61.3% to 76.4%. It was also determined that the use of fiber did not have a significant effect on compressive strength and unit weight. The results proved that it is possible to produce expanded glass aggregate-bearing lightweight geopolymer mortars with acceptable mechanical properties.

1. Introduction

Concrete is the most widely used construction material in the world [1]. A large amount of energy is consumed, and extensive quantities of CO_2 are emitted during cement production [2]. It is thought that the cement industry is responsible for 5-8% of the global CO_2 emissions [3]. It is crucial to develop sustainable materials that can reduce the economic and environmental drawbacks involved in producing cement [4].

Geopolymers are economic and environmentally friendly materials and have the potential to be an alternative to conventional concrete [5]. According to Davidovits [6], incorporating by-product slag into geopolymer as binder can result in an 80% reduction in CO_2 emissions and a 59% decrease in energy consumption compared to those of the portland cement. Geopolymers possess outstanding mechanical and durability properties [7], as well as high early strength [8], which makes them suitable for use in various application fields. Binder and concrete production, 3D printing technology, refractory materials, fiber-reinforced composites and decoration are some of these areas [9].

Various types of materials like fly ash, ground granulated blast furnace slag, kaolin and metakaolin can be utilized as aluminosilicate source

*Corresponding author: adilgultekin@duzce.edu.tr
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in geopolymer production. Commonly employed alkali solutions for geopolymerization include sodium silicate, potassium silicate, sodium hydroxide, and potassium hydroxide [10]. For the sake of curing, temperatures below 100°C are generally preferred [11].

Lightweight concrete serves the purpose of reducing the dead load and provides heat insulation in various construction materials, including masonry blocks, wall panels and other precast elements [12]. The advantages of lightweight concrete and geopolymers can be combined in lightweight geopolymer mixtures [13]. Lightweight geopolymer composites offer multiple benefits, such as good fire resistance, heat insulation and sound absorption [14]. It is possible to use natural lightweight materials such as volcanic tuff, perlite and vermiculite or artificial lightweight aggregates in the production of lightweight concrete [15].

Recycling and utilizing waste glass in various fields are essential for sustainability. The construction industry, in particular, holds a potential for the recycling of glass wastes. Ongoing studies explore the incorporation of glass powder and glass bead in the production of building materials. Recently, expanded glass aggregates have attracted attention and emerged as a potential area of use [16].

Expanded glass aggregate is manufactured by subjecting recycled waste glass to high-temperatures with the inclusion of various additives. The production process involves several stages, including expansion under high-temperature, cooling and screening. Due to its cellular structure, expanded glass aggregate has low thermal conductivity, density, and mechanical properties [17].

Numerous studies investigated the properties of cement-based concrete, mortar, and other composite materials, incorporating expanded glass aggregate. Seputyte-Jucike et al. [18] investigated the properties of expanded glass aggregate-bearing lightweight concretes and reported the possibility of achieving densities in the range of 247-335 kg/m^3. Bumanis et al. [19] conducted a study on some properties of lightweight concretes prepared with limestone powder and varying proportions of expanded glass as aggregate. The researchers observed that the fresh density of lightweight concretes containing expanded glass aggregate ranged between 647-809 kg/m^3, and the compressive strength of the concretes varied from 4.0 to 5.8 MPa. In a similar study, Bumanis et al. [20] examined the strength, density and alkali-silica reaction expansions of lightweight concrete prepared with expanded glass aggregate and eight different types of cements. Findings of this study indicated that the concrete mixtures exhibited a density within the range of 734-781 kg/m^3 and compressive strength ranging from 2.8 to 4.0 MPa.

While geopolymers offer numerous advantages, the production and properties of lightweight geopolymers using lightweight aggregates are the areas requiring further research [21]. Huiskes et al. [22] studied the impact of liquid/binder ratio, binder/aggregate ratio, aggregate gradation and alkali activator concentration on the strength, density and thermal properties of fly ash/blast furnace slag-based geopolymer mortars and concretes containing expanded glass aggregate. Humur and Cevik [23] investigated the influence of aluminosilicate type on the high-temperature resistance of PVA fiber-reinforced expanded glass aggregate-bearing geopolymer composites. Researchers reported that the compressive strengths of the geopolymer composites varied between 16.7 and 64.1 MPa, with a decrease of up to 79% upon exposure to 800°C. Priyanka et al. [24] explored the effect of inclusion of expanded clay aggregate instead of natural aggregate on the properties of fly ash-based geopolymer concretes and reported a gradual decrease in the compressive strength and density of concrete as the substitution ratio increased.

This study investigated the properties of fly-ash based geopolymer mortars prepared with expanded glass aggregate, as well as the influence of fiber addition on these mortars. For this purpose, the flow diameter, fresh unit weight, compressive strength, high-temperature resistance and water absorption tests were conducted. Basalt fiber was chosen as the fiber type due to its high-temperature resistant structure.

2. Material and Method

2.1. Materials

A Class F-fly ash was used as the aluminosilicate raw material. The chemical composition and some physical properties of the fly ash are given in Table 1. Lightweight mortars were produced using limestone aggregate (0-0.250 mm), expanded glass aggregate (various size fractions between 0.25 and 4 mm), activator and tap water. The images of expanded glass aggregates are given in Figure 1. Some physical properties and gradation of the limestone aggregate and combined aggregate are shown in Table 2 and Figure 2, respectively. Furthermore, a mixture labeled as "Ref" was produced using 0-4 mm limestone aggregate with a specific gravity of 2.60 and a gradation similar to that of the combined aggregate. Additionally, 6 mm-long basalt fibers were employed to assess the impact of fiber addition. Some

mechanical and physical properties of basalt fiber are given in Table 3.

A sodium silicate solution consisting of 9.25% Na_2O, 28.65% SiO_2, 62.10% water and a pellet-shaped sodium hydroxide with a purity of 98% were used to prepare the activator solution. The sodium hydroxide pellets were dissolved in the sodium silicate, and the solution was allowed to rest for 24 hours. The Ms ratio (the weight ratio of SiO_2 to Na_2O in the solution) and the amount of Na_2O (the weight ratio of Na_2O in the solution to the weight of fly ash) were 1.5 and 8%, respectively.

Table 1. Chemical composition and some physical properties of fly ash

Oxide	% (by weight)	Oxide/item	% (by weight)
SiO_2	55.9	TiO_2	1.0
Al_2O_3	23.3	P_2O_5	0.8
Fe_2O_3	6.3	Loss on ignition	2.0
CaO	5.3	Physical properties	
Na_2O	0.6	Specific gravity	2.21
K_2O	2.3	% retained on 32 µm	26.7
SO_3	0.2	% retained on 45 µm	20.0
MgO	2.1	% retained on 90 µm	6.4

Table 2. Some physical properties of aggregates

Property	Limestone aggregate	Expanded glass aggregate			
Particle size (mm)	0-4	0.25-0.50	0.50-1	1-2	2-4
Particle density (g/cm^3)	2.60	0.52	0.42	0.37	0.34
Water absorption (%)	1.2	20	18	18	15

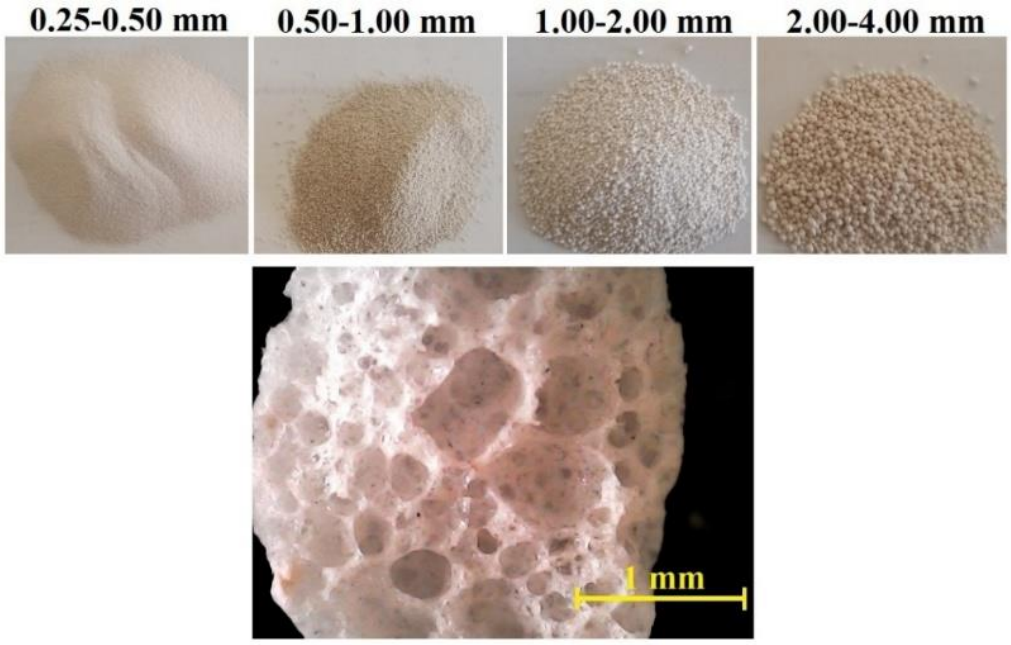

Figure 1. Expanded glass aggregate size fractions and porous structure of the broken aggregate particle

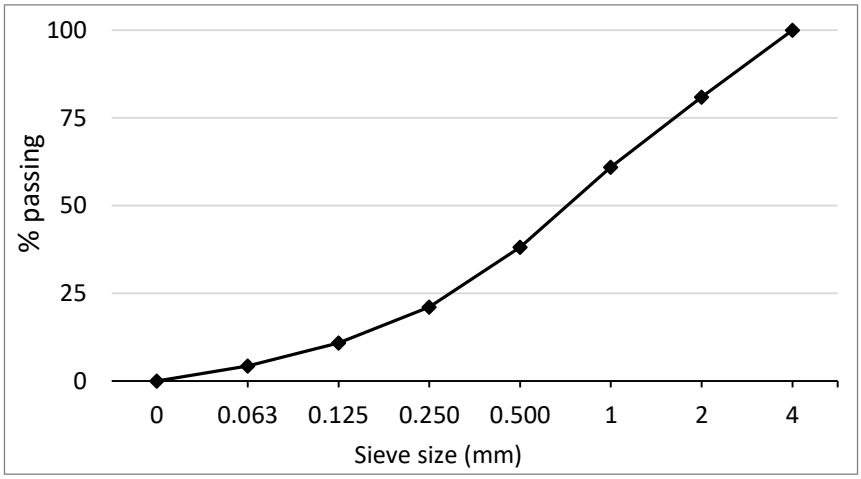

Figure 2. Gradation of limestone aggregate and combined aggregate

Table 3. Properties of basalt fiber

Properties	Value
Diameter (μm)	13-20
Modulus of elasticity (GPa)	88
Tensile strength (MPa)	4000-4500
Density (g/cm^3)	2.80

2.2. Method

Limestone and glass aggregates were used in the saturated-surface-dry and oven-dry conditions, respectively. In the production of lightweight mortars, the aggregates, water and fiber (if any) were mixed for 90 seconds at a speed of 62.5 rpm. Subsequently, fly ash and activator solution were introduced into the bowl. The mixer was operated for 90 seconds at the same speed, and the material adhered to the bowl was scraped off in approximately 15 seconds. Finally, the mixer was run for an additional 90 seconds at 125 rpm. The flow diameters of mortar mixtures were determined in accordance with TS EN 459-2 standard [25]. The mixtures were cast into 50 mm steel cube molds and compacted in two layers each with 25 jolts using a jolting table. The molded specimens were placed in the oven immediately after preparation and were cured for 24 hours at 90°C. At the end of the curing period, specimens were taken out of the oven and demolded after cooling to room temperature. The samples removed from the mold were immediately used for hardened state tests.

High-temperature resistance test was performed using a muffle furnace. The temperature rise rate of the furnace and exposing temperature were 10°C/minute and 900°C, respectively. The specimens were kept in the furnace at 900°C for 3 hours, which was followed by gradual cooling to the room temperature in the furnace.

The compressive strength tests were conducted using a 500 kN mortar press at a constant loading rate of 0.9 kN/s. The reported strength values are the average of 3 specimens. Equation 1 was used to calculate the compressive strength (σ_c in MPa). In this formula P represents the maximum load (N) and A represents the cross-sectional area (mm^2) of the specimen.

While determining the unit weights, the weight of fresh mortar that completely filled the 50x50x50 mm mold was determined after compaction process and fresh unit weights in m^3 were calculated.

For water absorption determination, the samples cooled to room temperature after curing were used. The samples were kept in tap water for 48 hours, then the surfaces of the samples taken out of the water were dried with a towel and their saturated-surface-dry weights were measured. The samples were kept in the oven at 105°C until they reached a constant weight, and their oven-dry weights were determined. The water absorption of mortar samples was determined according to Equation 2. W_{ssd} and W_d represent saturated-surface-dry and oven-dry weights, respectively.

$$\sigma_c = \frac{P}{A} \quad (1)$$

$$Water\ absorption\ (\%) = \frac{W_{ssd} - W_d}{W_d} x100 \quad (2)$$

Photographs of the performed tests are presented in the Figure 3.

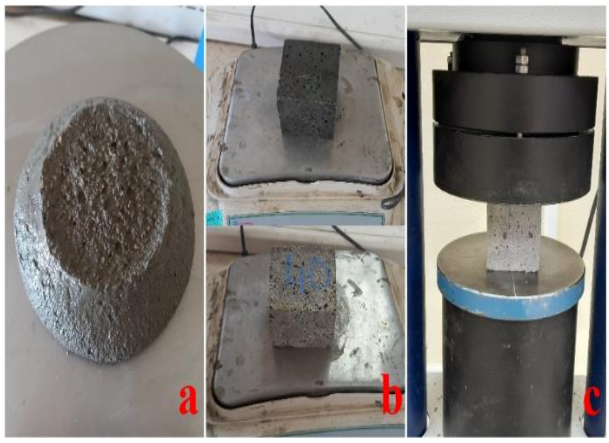

Figure 3. Photographs of tests (a: flow diameter test, b: weighing of specimens to determine water absorption, c: compressive strength test)

2.3. Mixtures

Within the scope of the study, five mixtures were prepared. The first was the reference mixture produced with limestone aggregate (0-4 mm) and denoted as "Ref." The other mixtures were plain and fiber-reinforced lightweight mortars prepared using limestone aggregate (0-0.25 mm) and various sizes of expanded glass aggregate (0.25-0.50, 0.50-1, 1-2, and 2-4 mm). The lightweight mortars were labeled according to the fiber dosage. For example, LW-0.1 designates the lightweight mortar mixtures containing 0.1 volume % fiber.

The proportions and flow diameters of the mixtures are given in Table 4. In order to obtain comparable flow to that of the reference mix, more water was added to the LW-0 mixture.

3. Results and Discussion

3.1 Unit Weight and Water Absorption

The fresh unit weight and water absorption values of the hardened mixtures are given in Figure 4. As expected, the fresh unit weights of mortar mixtures containing expanded glass were lower than that of the reference mixture due to the difference in the specific gravities of the aggregates. As a result of the lightweight nature of expanded glass, fresh unit weights of the lightweight mortars were approximately half of that of the reference mixture, ranging from 1021.4 to 1028.3 kg/m^3. The difference in density between limestone and expanded glass aggregate was the main cause of the decrease in unit weight. The extensive porous structure of the expanded glass aggregate, illustrated in Figure 1, contributes significantly to this phenomenon. Additionally, the uniformity in size among the expanded glass aggregates within a given size fraction adversely impacts compactness. Therefore, a decrease of up to 53% in unit weights was observed. In a similar investigation, Mermertas et al. [26] employed fly ash- and Portland cement-based artificial lightweight aggregate in preparation of fly ash-based lightweight mortar and reported that replacing of natural sand with lightweight aggregate resulted in a 17.5% reduction in the fresh density of the mortar Tayeh et al. [27] examined the effect of substituting pumice and expanded clay aggregate with coarse dolomite aggregate on the properties of fly ash-based geopolymer concrete. Researchers reported that the unit weight of hardened concrete decreased by approximately 20% and 22%, respectively, with the use of expanded clay and pumice aggregate.

Table 4. Proportions and some properties of mixtures

Ingredient/property	Ref	LW-0	LW-0.1	LW-0.2	LW-0.4
Fly ash (g)	420	420	420	420	420
Activator (g)	197	197	197	197	197
Water (g)	68	90	90	90	90
0-4.0 mm (Limestone) (g)	1202.6	-	-	-	-
0-0.25 mm (Limestone) (g)	-	24.2	24.2	24.2	24.2
0.25-0.50 mm (Expanded glass) (g)	-	19.6	19.6	19.6	19.6
0.50-1 mm (Expanded glass) (g)	-	26.2	26.2	26.2	26.2
1.0-2.0 mm (Expanded glass) (g)	-	22.9	22.9	22.9	22.9
2.0-4.0 mm (Expanded glass) (g)	-	21.8	21.8	21.8	21.8
Basalt fiber (g)	-	-	2.35	4.70	9.40
Flow diameter (cm)	15.0	14.9	14.5	13.7	13.1

The incorporation of basalt fiber demonstrated negligible impact on unit weight values. Due to reduced workability resulting in insufficient compacting, the mortar with the highest fiber dosage exhibited the lowest fresh unit weight among the samples. However, the differences between the unit weights of lightweight mixtures was insignificant. Water absorption test results revealed that samples containing expanded glass aggregate absorbed 97%-105% more water than the reference mixture. It is known that lightweight aggregates absorb higher amounts of water compared to the conventional natural aggregates used in concrete production due to their porous structure [17]. In lightweight mortars, some of the absorbed water was attributed to the water absorption capacity of expanded glass aggregates. Moreover, even though the aggregate gradations are the same, the similarity in grain sizes within specific size fractions of the expanded glass aggregate is another contributing factor to the formation of voids in the mixture.

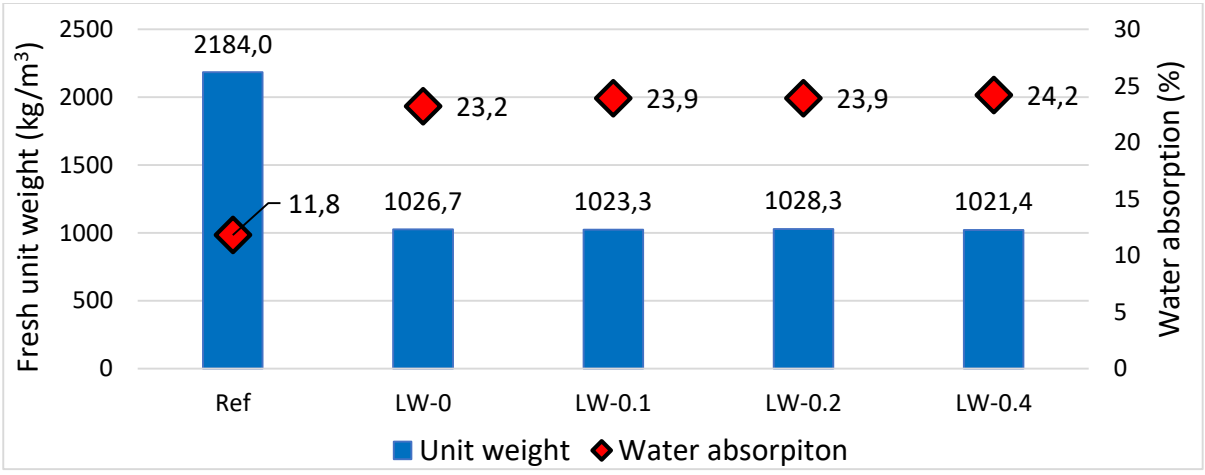

Figure 4. Fresh unit weight and water absorption of mortar mixtures

3.2. Compressive Strength

The compressive strengths of mortars are presented in Figure 5. The reference mixture containing entirely limestone aggregate demonstrated the highest strength as 31.9 MPa. With the addition of fiber to an optimum dosage (0.2%), the compressive strength of lightweight mortar mixtures increased slightly. Beyond the optimum level of fiber, the strength decreased slightly, probably due to the reduced workability. The compressive strengths of fiber-free lightweight mortar and mortars containing 0.1, 0.2 and 0.4% fiber were 8.2, 8.9, 9.0 and 8.0 MPa, respectively. Substituting limestone aggregate with expanded glass aggregate resulted in a decrease in compressive strength ranging from 71.8% to 74.9%. The main reason for this outcome is the low strength of glass aggregate attributable to its cellular structure. In a similar study, Priyanka et al. [24] stated that the substituting of natural coarse aggregate with expanded clay aggregate reduces the compressive strength, and with the increase in the substitution ratio, the strength losses escalated to higher levels. Elrahman et al. [28] reported that the compressive strengths of cement-based lightweight concretes produced with expanded glass and expanded clay varied between approximately 7-18 MPa, depending on the mixture design.

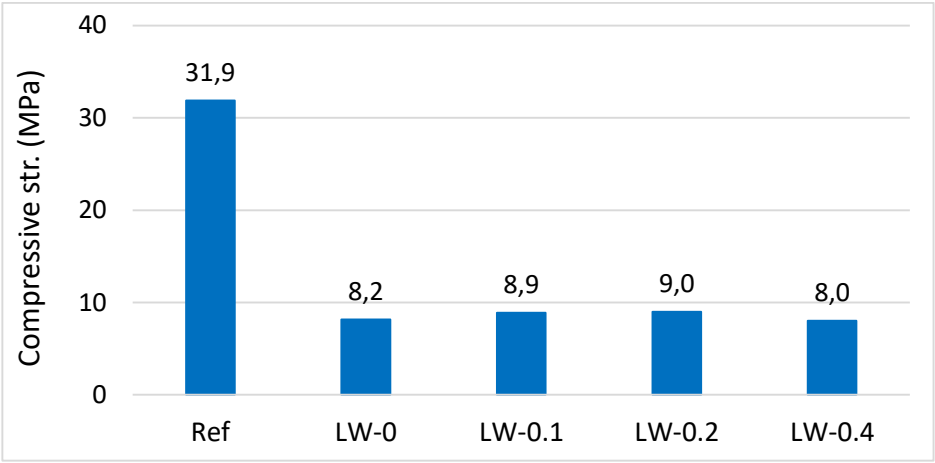

Figure 5. Compressive strength of mortar mixtures

3.3. High Temperature Resistance

Photographs of the samples before and after exposure to the high-temperature are shown in Figure 6. Despite the absence of any visible damage or cracks in any of the specimens, the color of the samples changed from gray to a slightly reddish hue due to the influence of elevated temperature. Similar color changes were observed in fly ash-based geopolymers by Hager et al. [29] and R. Zhao and Sanjayan [30], and researchers attributed this transformation to the oxidation of iron components. The broken cross section of a samples before and after being exposed to 900°C, followed by crushing in compression, is shown in Figure 7. It was observed that the expanded glass aggregate particles, melted under the influence of high temperature, resulted in pore formation in the areas originally occupied by the solid aggregate particles before the high-temperature tests. The expanded glass aggregates and pores formed by the aggregate melting are showed with black and red circles, respectively in Figure 7.

Figure 6. Pictures of specimens (a: before high-temperature test, b: after high temperature test)

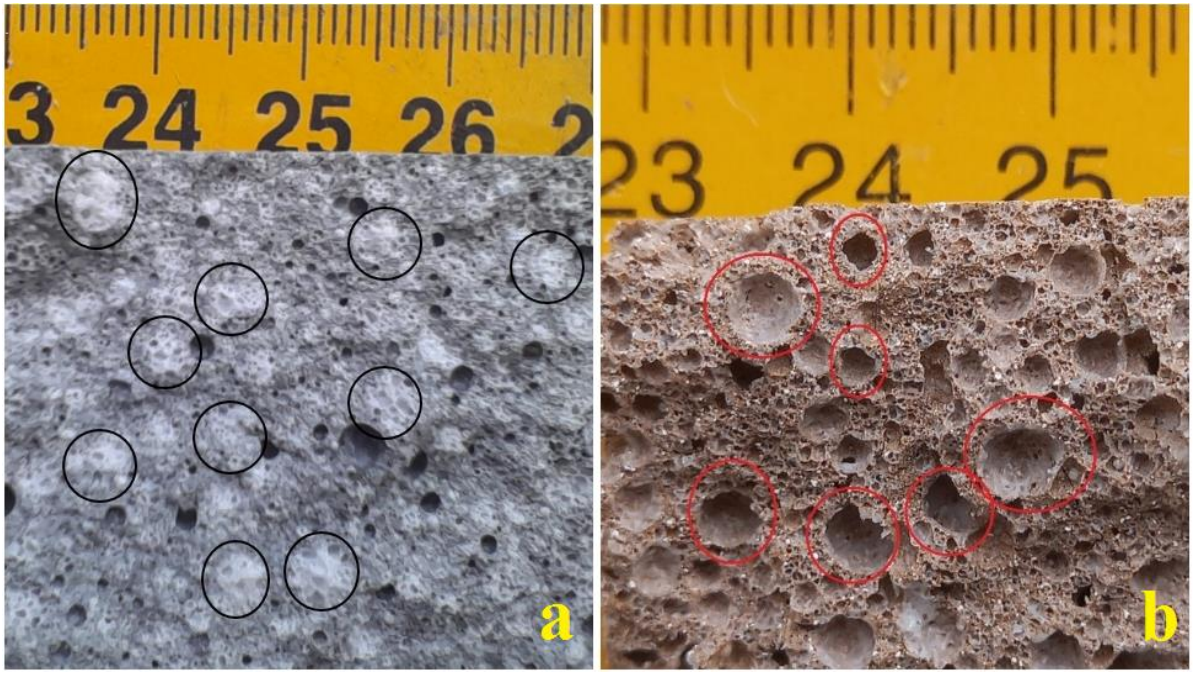

Figure 7. Broken cross-section of a compression test specimens (a: before and b: after exposure to high-temperature)

The compressive strength and relative strength values of mortars exposed to 900°C are given in Figure 8. Following the high-temperature test, two opposite outcomes were observed. The compressive strength of the reference mixture decreased by 39.8%, whereas the opposite trend was seen in lightweight specimens. The strengths of fiber-free lightweight mixture and fiber-reinforced mortars containing 0.1, 0.2 and 0.4% basalt fiber increased by 73.2%, 76.4%, 65.6% and 61.3%, respectively. Diverse factors play a role in the occurrence of these two conflicting situations.

The evaporation of both physically and chemically bound water in the geopolymer samples may result in thermal shrinkage and cracking at elevated temperatures. Additionally, the vapor pressure may cause internal stresses which adversely affect the structure, and the extent of damage is closely related to the pore structure [31]. The vapor pressure, which cannot be evacuated easily from dense structures, leads to severe damage [32]. Obviously, this was not the case in the porous (lightweight) mixtures used in this study.

In addition to the microstructure of the matrix, the high-temperature resistance is also influenced by the thermal expansion coefficient of the aggregate [33]. Rickard et al. [34] investigated the compressive strength and microstructure of two different geopolymer pastes exposed to elevated temperatures. The researchers reported a significant reduction in the compressive strength of the paste with high initial compressive strength and low permeability after exposure to the elevated temperatures. In contrast, compressive strength of the paste with low initial compressive strength and a more porous structure improved from approximately 30 MPa to about 90 MPa. Researchers also noted that upon increasing the temperature, the water vapor could be more easily evacuated from the low-strength samples, the newly formed crystalline compounds may cause less damage due to porous structure of the sample. Payakaniti et al. [35] investigated the effect of high temperatures on Class C fly ash-based geopolymers and stated that new crystalline products formed in the matrix at and beyond 800°C temperature may contribute to the strength of the mixture with filler effect. However, as their quantity increases, internal stresses occur in the matrix, which affect the strength adversely. In this study, glass aggregate particles in lightweight mortars were partially or completely melted at high temperature. It is thought that the voids formed by the fusion of glass particles provide sufficient space for the newly formed phases, preventing/reducing formation of the internal pressure and subsequent hazardous internal stresses.

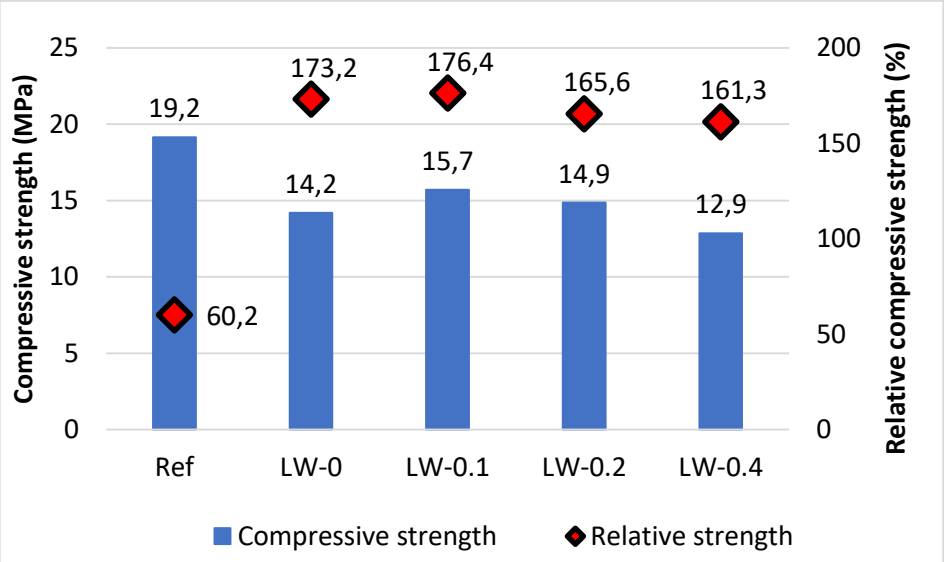

Figure 8. Compressive strengths and relative strengths of mortar mixtures after high-temperature effect

4. Conclusion

In this study, the properties of fly ash-based geopolymer mortars prepared with expanded glass aggregate and the effect of fiber addition on these mixtures were investigated. Based on the materials used and tests applied, the following conclusions can be drawn:

The fresh unit weight of the conventional geopolymer mortar produced with limestone aggregate was 2184 kg/m³. As expected, the unit weight of the mortar decreased by about 53% with the use of glass aggregate. Addition of basalt fibers had not a significant effect on the unit weight of the mixture.

The compressive strength of the conventional geopolymer mortar produced with limestone aggregate was 31.9 MPa, whereas the compressive strengths of mortars prepared with expanded glass aggregate varied between 8.0 and 9.0 MPa, depending on the fiber content. While there was a slight increase in compressive strengths with fiber addition up to a volume fraction of 0.2%, it can be said that inclusion of basalt fiber did not have a significant effect on the compressive strength.

As a consequence of the mortar's pore structure and the high water absorption of expanded glass aggregate, the water absorption of lightweight mortar mixtures was significantly higher than that of the reference sample. Additionally, due to the decrease in workability, water absorption values increased slightly with the addition of fiber.

Upon exposure to 900°C, compressive strength of the mortar prepared with limestone aggregate decreased by approximately 40%, while the strength of lightweight aggregate-bearing mortars increased considerably. These increases were 73.2%, 76.4%, 65.6%, and 61.3% for fiber-free lightweight mortar and mortars containing 0.1%, 0.2%, and 0.4% fiber, respectively. It is thought that the voids formed by the fusion of glass particles provide sufficient space for the newly formed phases, preventing/reducing formation of the internal pressure and subsequent internal stresses which may cause micro cracking in both matrix and interfacial transition zone.

The investigation of the strength and -especially- durability properties of geopolymer mortars and concretes produced using expanded glass aggregate is still a topic that needs further research. The effect of cooling regime after exposure to high temperature on the properties of lightweight geopolymer systems is also of interest.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

This paper represents the extended full text of the study presented as an oral presentation at the “5th International Conference on Natural and Applied Science and Engineering” and published as an abstract in the abstract booklet.

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